Senior Thesis

Petrography and Trace-Element Geochemistry of Metabasalts on Diego Ramirez Islands, southern Chile

by

Mark Emslie

1988

Submitted as partial fulfillment of
the requirements for the degree of
Bachelor of Science in Geology and
Mineralogy at The Ohio State University,
Winter Quarter, 1988

Approved by:

Richard E. Hanson

Dr. Richard E. Hanson

Abstract

The purpose of this paper is to determine the original igneous setting of metabasalts on the Diego Ramirez Islands, which are a group of islands located about 100 km southwest of Cape Horn, in the southernmost part of Chile. These islands are located where the western edge of South America's continental shelf intersects the Shackleton Fracture Zone. The islands, which are thought to represent material accreted in an ancient subduction zone along the continental margin, are complicated because of metamorphic and tectonic effects. The islands consist of two main rock units - metabasalt and tectonic melange. The presence of pillow structure and high vesicularity in the metabasalts indicates these rocks were formed in a shallow-marine environment. The petrography, based on the presence of titanaugite and absence of orthopyroxene, indicates the original igneous material was alkali-olivine basalt. This composition provides evidence for a seamount environment. Metamorphic assemblages include crossite, pumpellyite, chlorite, white mica, epidote, albite, and prehnite, but lawsonite is absent. The assemblages indicate high pressure/low temperature metamorphism that is transitional between blueschist, greenschist, and prehnite-pumpellyite facies. Metamorphic conditions were approximately 5.5 kbars and 270°C. The geochemical analysis of the elements Rb, Sr, Zr, Y, Cr, Ni, and Ti, using x-y graphs to test mobility and discrimination diagrams to test environmental setting, indicates that these rocks were originally erupted in a seamount setting. Rb and Sr were mobilized during low-grade metamorphism.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

Introduction

This study deals with metabasalts located on the Diego Ramirez Islands, southern Chile (Figs. 1 & 2). The Diego Ramirez Islands consist of metabasalts and tectonic melange, which have been deformed and metamorphosed during subduction, uplift, and faulting. The location of these islands is about 100 km southwest of Cape Horn, where the Shackleton Fracture Zone intersects the western edge of South America's continental shelf (Fig. 1). The islands are thought to represent the southernmost exposures of forearc material produced along the western edge of South America during subduction (Wilson and others, in press).

Geologic Setting

Regional Tectonic Setting

Rocks exposed on the Diego Ramirez Islands, South Orkney Islands, South Shetland Islands, and the northern tip of the Antarctic Peninsula formed during subduction-related accretion and sedimentation in forearc environments along the Pacific margin of Gondwanaland (Dalziel, 1984). The paleosubduction zone roughly follows the present Pacific coastline of South America and the Antarctic Peninsula. These forearc terrains represent both exotic oceanic crustal material that has been accreted within the subduction zone and volcaniclastic flysch-like sequences deposited in forearc basins (Forsythe, 1982). The Diego Ramirez Islands are important when reconstructing the Pacific margin of the Gondwana supercontinent. The Diego Ramirez Islands lie at the northern end of the Shackleton Fracture Zone, while the Elephant/Clarance Island group, in the South Shetland Islands, lies at the southern end of this fracture zone. Both groups of islands contain high pressure/low temperature metamorphic rocks (Wilson and others, in press). This implies that deep levels of the Gondwanide accretionary complex in the Scotic Arc region may have been uplifted by Cenozoic fracture zone tectonics (Dalziel, 1984).

Geology of the Islands

There are two groups of islands that make up the Diego Ramirez Islands. These are the northern group, which consists only of metabasalts (Fig. 3), and the southern group, which consists of two main islands and several smaller islands (Fig. 4). The islands of the southern group consist of two principal rock units: metabasalt and tectonic melange. The metabasalts occur predominantly as large, fault-bounded masses of pillow breccia with less abundant pillow lava and some highly deformed undifferentiated metabasalts. In some areas thick, massive pillow breccia units are separated by thin tuff horizons.

The tectonic melange is divided into three types. Phyllite-metabasalt melange is the most abundant of the three and consists of dark grey phyllite surrounding phacoidal masses of pillow lava and breccia; thin basaltic tuff layers are interlayered with the phyllites. Phyllite melange contains angular to subrounded blocks or tectonic inclusions of metabasalt and less abundant ribbon chert, sandstone, and limestone set in a phyllitic matrix. Chert-metabasalt melange is least abundant and consists of metabasalt tectonically intermixed with reddish ribbon chert (Wilson and others, in press; Dalziel, 1983; Davidson and others, in press). The rock characteristics are important in determining the original depositional environment. The thin tuff layers and ribbon chert are evidence of a submarine environment, as is the abundance of pillow breccia and pillow lava within the metabasalts.

The deformation of these rocks involved several generations of ductile and brittle structures that were produced during tectonic mixing and melange formation at different levels in the subduction complex. There are three phases of ductile deformation recognized that produced a foliation in the phyllites and a flattening fabric in the metabasalts. Mylonites and kink structures also were produced (Wilson and others, in press). These ductile fabrics were developed at relatively high pressure during shearing within the zone of underplating in the accretionary prism (Dalziel, 1984; Meneilly and Storey, 1986). The melange was developed during subduction-related deformation. Cataclastic fault zones on the islands post-date the ductile deformation. The cataclasis disrupted the earlier ductile fabrics, causing dispersion of more competent blocks within a sheared phyllitic matrix. These fault zones caused a major episode of melange formation. Phyllites at Clarkson Point on Isla Gonzalo give a 169.3 $\pm$ 16 m.y. isotopic age on a four point Rb-Sr errorchron (Davidson and others, in press). This may date the time of subduction-related metamorphism.

Objectives

The large volume of pillow breccia relative to pillow lava within the Diego Ramirez metabasalts makes them similar to seamount volcanic sequences. Based on this, Wilson and others (in press) suggested the metabasalts represent parts of a dismembered seamount that was underplated, metamorphosed, and incorporated into the accretionary complex during subduction.

The main objective of this study is to test the seamount hypothesis by studying evidence for the original site of eruption of the basalts. This is done using two lines of evidence: petrographic features and geochemical data obtained from the samples. Another objective of this study is to examine the metamorphism of the metabasalts and determine the pressure-temperature conditions of metamorphism.

Procedures

The samples that were analyzed were collected by R. Hanson and others during two separate expeditions to the Diego Ramirez Islands, in 1985 and 1986. The analyzed samples include 19 pillow samples (samples 3-FC, 3-FCON, and 3-FR are from one pillow) and one gabbro collected from a tiny island east of Isla Bartolome. Sample localities are shown in Figures 3 and 4.

The petrographic procedures involved cutting thin section chips perpendicular to pillow rims, where the transition from rim to core could be seen and fractures were absent. The only exceptions were sample 3-FC, which was a chip of the pillow core only, and sample 3-FR, which was a chip of the rim only. The chips were then made into thin sections, which were studied under a microscope to determine the data given in Table I.

Preparation of samples for geochemical analysis involved strict controls on contamination. Large pillow samples (up to 5 kg) were first broken into cm-sized fragments with a sledge hammer. Fragments of basalt that were not weathered, altered, or highly veined were kept for analysis, all other fragments being discarded. The samples were cleaned with a brush and then further broken into .5 cm fragments using a jaw crusher. A representative split of this material weighing about 10g was obtained using a mechanical separator into which the sample was poured. This split was then reduced to a fine powder in a disc mill. Between each sample, both the jaw crusher and the disc mill were cleaned, precontaminated with a split of the sample, and then cleaned again. In addition, residual powder that collected in the disc mill was removed by powderizing SiO_2 pellets in the mill between sample runs.

Nineteen samples of pillows and one sample of a gabbro, 20-B, were analyzed for Rb, Y, Sr, Zr, Cr, Ni, and Ti by x-ray fluorescence spectrometry on pressed-powder pellets at the University of Houston. The analytical technique followed Norrish and Chappell (1967). The results are compiled in Table II. The precision, the difference between repeated analyses of the same sample, was < 5% for Zr, 5% for Sr, Y, Rb, and Ni, 10% for Cr, and .96% for TiO_2. The accuracy, the difference between the analyzed value and the recommended value for U. S. Geological Survey standards, was < 5% for Zr, Sr, Y, and Ni, 10% for Cr, 10% for Rb, and 1-1.5% for TiO_2. The TiO_2 values were analyzed in wt.% and then converted to Ti in ppm. Sample 3-FR, from a pillow rim, could not be analyzed by x-ray flourescence spectrometry due to swelling of the powder when making the pellet, but this sample was analyzed by petrography.

Petrography

Results of the petrographic analysis are given in Table I. The petrographic features shown by the metabasalts can be used to reconstruct the original igneous and metamorphic conditions.

Igneous Features

Phenocrysts of olivine (pseudomorphed), clinopyroxene, plagioclase, illmenite, and magnetite were found in the samples. Most of the samples contain large amounts of plagioclase and clinopyroxene phenocrysts. Pseudomorphed olivine is present in samples 71 and 31-B, while large illmenite phenocrysts are present in samples 5-H and 1-B. Sample 81 shows a glomeroporphyritic texture. Titanaugite is abundant in many samples and was recognized from its distinctive pleochrism. The gabbro (sample 20-B) contains abundant plagioclase replaced by white mica. Apatite, illmenite, clinopyroxene, and red-brown biotite also are present. This sample completely lacks amgydules, and has only a minor amount of veinlets.

The groundmass of the pillow lavas contains abundant quench structures shown by illmenite, clinopyroxene, and plagioclase. The quench plagioclase crystals are acicular hollow prisms elongated parallel to a (Bryan, 1972). These crystals, if cut along the long axis, show shallow-tail structures, while if cut perpendicular to the long axis show belt-buckle structures. The illmenite quench structures appear as aggregates of radiating small needles, while the clinopyroxene structures are radiating aggregates of acicular crystals. Sample 3-FC, taken from the outermost part of a pillow rim, consists mostly of chlorite plus some white mica, representing replacement of original quenched glass.

The textures in these samples depend on the position relative to the rim of the pillow. The outer part of the rim contains the largest amount of quench textures, which gradually decrease toward the core, where intersertal textures are present.

The pillow lavas are generally rich in amygdules up to 2 cm in diameter, with some of the amygdules being aligned by the flow of lava. One sample has a diktytaxitic texture, which is produced when the lava contains very abundant microvesicles between crystals in the groundmass. The high volume of vesicles, the relatively large diameter of some of the vesicles, and the diktytaxitic texture indicate an original shallow-marine environment of eruption (Jones, 1969; Moore, 1965).

The distinction between alkali-olivine basalt and tholeiitic basalt, the most common basalt, can be determined using petrographic features. Alkali-olivine basalts may contain biotite, apatite, and titanaugite in the groundmass while tholeiitic basalts usually contain orthopyroxene, augite, and devitrified glass with a high content of quartz (Ehlers and Blatt, 1982; Williams and others, 1982; Hyndman, 1985). The Diego Ramirez metabasalts appear to be alkali-olivine basalts based on the abundance of clinopyroxene, the complete absence of orthopyroxene, and the presence of titanaugite, which is only found in alkaline rocks (Williams and others, 1982). This supports a seamount setting as the original site of eruption of the metabasalts, because alkali-olivine basalts are characteristically found in seamounts.

The gabbro (sample 20-B) also appears to have alkaline affinities, based on the presence of some biotite, the relative abundance of apatite, and the lack of orthopyroxene.

Groundmass nepheline and olivine are characteristic of alkali-olivine basalts. They are probably absent in the Diego Ramirez metabasalts because these minerals are highly unstable during low-grade metamorphism. The low abundance of olivine phenocrysts in these samples may be due to the fact that they have undergone some crystal-liquid fractionation, with loss of olivine.

Metamorphic Features

The samples in general lack a strong foliation, although the amygdules are tectonically flattened in some. Most of the foliation observed in the field is seen to wrap around the pillows (Hanson, personal communication).

The metamorphic minerals present can be used to estimate conditions of metamorphism. Since different minerals form at certain pressures and temperatures, the minerals present in the pillow lavas can be used to determine the pressures and temperatures that affected the lavas during metamorphism.

Igneous rocks that have been metamorphosed in the blueschist facies contain lawsonite, glaucophane/crossite, pumpellyite, and chlorite; rocks in the greenschist facies contain chlorite, actinolite, white mica, epidote, and albite; and rocks in the prehnite-pumpellyite-metagraywacke facies contain prehnite and pumpellyite (Ehlers and Blatt, 1982).

In the Diego Ramirez metabasalts the presence of stilpnomelane, white mica, chlorite, albite, epidote, and pumpellyite (Table I) indicates low-grade metamorphism. Wilson and others (in press) also found crossite in the metabasalts, but no lawsonite was detected either petrographically or by x-ray diffraction. This indicates that conditions approached, but did not reach, the blueschist facies, since lawsonite is absent. One sample (sample 81) contains prehnite and pumpellyite. The mineral assemblages therefore indicate a comparatively high pressure/low temperature metamorphism, probably transitional between blueschist, greenschist, and prehnite-pumpellyite-metagraywacke facies with a pressure of about 5.5 kbars and a temperature of about 270°C (Fig. 5). This relatively high pressure/low temperature metamorphism occurred during subduction while these rocks were being underplated (Fig. 6). The rocks were then upfaulted to the surface in the accretionary prism (Fig. 7).

Geochemistry

Most of the samples are fairly similar in trace element composition (Table II). However, three samples are different from the rest. Sample 1-B has extremely high Zr, the highest Y, and the lowest Cr and Ni concentrations. In basaltic systems Zr and Y are incompatible elements so they are concentrated in the magma during fractionation. Cr and Ni on the other hand are highly compatible. These characteristics indicate that 1-B is highly fractionated with respect to the other samples. Sample 76-1 is different from the other samples in that it has the lowest TiO_2 and Zr contents. This sample will be discussed in more detail later. Sample 20-B (the gabbro) has the highest TiO_2, very low Cr, and fairly low Ni contents. This indicates that this sample was derived from another relatively highly fractionated magma.

Trace elements in metabasalts can be used to determine the original tectonic environment of eruption. This technique, however, is valid only if the elements have been immobile during metamorphism (i.e., their contents have remained unchanged). Immobility can be determined using x-y graphs of two different elements. The idea is that in a series of genetically related basalts, igneous processes will produce linear arrays on such graphs. If such linear arrays are preserved during metamorphism, it is assumed the elements have behaved in a relatively immobile fashion.

The correlation coefficient (r) is used to determine to what extent the data approach a line on plots of one element versus another ($r=1$ is a straight line). Correlation coefficients are given in Table III. Graphs of Ni vs. Cr, Y vs. Zr, and Y vs. Ti for the Diego Ramirez metabasalts define linear arrays ($r>0.5$), and therefore Cr, Ni, Y, Zr, and Ti are considered to have been relatively immobile (Figs. 8-10). Some other plots of these elements relative to each other would have an (r) value between 1 and .5 if one or two anomalous points are taken out (Figs. 11-17). The anomalous points in these graphs are generally 20-B (the gabbro) and 1-B. These samples appear to have different original igneous compositions (as already discussed). Sample 76-1 also is anomalous on some plots. This is also probably due to an original difference in composition, based on the fact that the abundance of the immobile elements is different from the other samples. If these anomalous points were excluded from the plots of Y vs. Ti and Y vs. Zr there would be a significant increase in the correlation.

The graph of Rb vs. Sr shows a complete scatter of points, indicating that these elements were highly mobile during metamorphism (Fig. 18). Rb and Sr also show poor correlation when plotted versus the immobile elements ($r<.5$ in all cases), thus further confirming the mobility of Rb and Sr in the metabasalts (Figs. 19-26). Some of these graphs (for example Zr vs. Rb, Y vs. Rb, Cr vs. Sr, and Zr vs. Sr) show a vague linear relationship, especially when the anomalous samples (1-B, 20-B, and 76-1) are excluded. This indicates that some of the original igneous variations have been preserved even in the mobile elements.

Ti, Zr, Y, Cr, and Ni are usually immobile during low-grade metamorphism of basalts, which is consistent with the present results (Pearce, 1982; Leat and others, 1986; Pearce and Norry, 1979; Hyndman, 1985). Rb and Sr, on the other hand, are typically mobile in metabasalts, as in the present case.

Basalts erupted in within-plate tectonic settings can be identified from Ti-Zr-Y, Zr/Y vs. Zr, and Cr-Y discrimination diagrams (Pearce and Cann, 1973; Pearce and Norry, 1979; Pearce, 1982). In the Ti-Zr-Y discrimination diagram all the samples but two plot in the within-plate basalt region (Fig. 27). This is also true in the Zr/Y vs. Zr diagram (Fig. 28). In the Cr vs. Y discrimination diagram, most samples plot very near or in the within-plate basalt region, with two samples further from the region than the others (Fig. 29). The within-plate field in these diagrams includes both ocean-island (seamount) basalts and continental flood basalts. A continental flood basalts setting is not consistent with the abundance of pillows and occurrence within a subduction complex. Thus, the discrimination diagrams indicate a seamount as the original site of eruption.

The same two samples (1-B and 76-1) are the anomalous points on all three diagrams. 1-B is highly fractionated as mentioned before, which is probably why it plots in an anomalous fashion. The reason for the deviation of sample 76-1 is uncertain. It plots in the ocean-floor basalt fields in the Ti-Y-Zr and Zr/Y vs. Zr diagrams. The high vesicularity in the sample contradicts this, however, and the significance of this sample remains unclear. Sample 20-B (the gabbro) also plots in a different fashion from the other samples. This is high in Ti and may be partly cumulate in origin. The sample was derived from a highly differentiated liquid like sample 1-B.

Conclusion

Determining the original environment of eruption of the Diego Ramirez metabasalts is complicated by the metamorphism and tectonism that have affected the rocks. The Diego Ramirez Islands lie within an old subduction zone that was located along the Pacific margin of South America. These islands consist of two main rock units - metabasalts and tectonic melange. The metabasalts show high vesicularity and a large volume of pillow breccia relative to pillow lava. They are associated with ribbon chert layers and thin tuff horizons. These characteristics suggest a within-plate seamount as the original setting of eruption of the basalts. The high percentage of vesicles indicates that the lavas were extruded in a shallow-marine environment (i.e., a seamount). The petrography of these rocks, including the presence of titanaugite and the absence of orthopyroxene, indicates that the original igneous material was alkali-olivine basalt. The gabbro also shows alkaline affinities. This is further evidence for a seamount as the site of eruption.

Plots of the trace elements Rb, Sr, Zr, Y, Cr, Ni, and Ti on x-y graphs indicate that Rb and Sr were mobile during metamorphism, while Zr, Y, Cr, Ni, and Ti were relatively immobile. Tectonic discrimination diagrams using the immobile elements show that the metabasalts were originally formed in a seamount setting, which is consistent with the petrographic evidence.

The assemblage of metamorphic minerals present indicates that metamorphism was transitional between the blueschist, greenschist, and prehnite-pumpellyite-metagraywacke facies, with pressures of about 5.5 kbars and temperatures of about 270°C.

The history of the Diego Ramirez Islands begins with alkali-olivine basalts being erupted in a seamount setting, with chert and tuff beds surrounding the seamount, south or west of the present position of the islands. Subduction under the South American plate carried the seamount into the subduction zone, and caused the seamount basalts to become attached to the overriding plate during underplating. At this depth, metamorphic conditions approached the blueschist facies. Shearing and tectonic intermixing of basalt and other rock types in this zone produced melange material that was later uplifted by faults to higher levels within the accretionary complex.

Acknowledgements

I would like to thank Dr. Donald Elthon from the University of Houston for analyzing the samples for trace elements, Dr. Richard E. Hanson from the Ohio State University for his constructive criticism of the drafts and assistance with the petrologic data, and Rodney A. Sheets and Ken Johnson for their help with the graphs and diagrams.

Works Cited

Bryan, W. B., 1972, Morphology of quench crystals in submarine basalts: Journal of Geophysical Research, v. 77, n. 29, p. 5812-5819.

Dalziel, I. W. D., 1983, Geologic transect across the southernmost Chilean Andes report of R/V Hero cruise 83-4: Antarctic Journal of the United States, v. 18, n. 4, p. 8-12.

Dalziel, I. W. D., 1984, Tectonic evolution of a forearc terrane, southern Scotia Ridge, Antarctica: Geological Society of America Special Paper 200.

Davidson, J., and others, Lower Mesozoic accretion of high bouyancy guyots on the Gondwanaland margin: Diego Ramirez Islands, southernmost South America: Revista Geologia de Chile, (in press).

Ehlers, E. G., and Blatt, H., 1982, Petrology: igneous, sedimentary, and metamorphic: San Francisco, W. H. Freeman and Company.

Forsythe, R. D., 1982, The late Paleozoic to early Mesozoic evolution of southern South America: a plate tectonic interpretation: Journal of the Geological Society of London, v. 139, p. 671-682.

Hyndman, D. W., 1985, Petrology of igneous and metamorphic rocks: New York, McGraw-Hill Book Company.

Jones, J. G., 1969, Pillow lavas as depth indicators: American Journal of Science, v. 267, p. 181-195.

Leat, P. T., Jackson, S. E., Thorpe, R. S., and Stillman, C. J., 1986, Geochemistry of bimodal basalts-subalkine/peralkine rhyolite province within the Southern British Caledonides: v. 143, p. 259-273.

Meneilly, A. E., and Storey, B. C., 1986, Ductile thrusting within subduction complex rocks on Signy Island, South Orkney Islands: Journal of Structural Geology, v. 8, p. 457-472.

Moore, J. G., 1965, Petrology of deep-sea basalt near Hawaii: American Journal of Science, v. 263, p. 40-52.

Norrish, and Chappell, 1967, Physical methods in determinative mineralogy: New York, Academic Press, p. 161-214.

Pearce, J. A., 1982, Trace element characteristics of lavas from destructive plate boundaries, *in* Thorpe, R. S., ed., Andesites-orogenic andesites and related rocks: New York, John Wiley, p. 525-548.

Pearce, J. A., and Cann, J. R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analyses: Earth and Planetary Science Letters, v. 19, p. 290-300.

Pearce, J. A., and Norry, M. J., 1979, Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks: Contributions to Mineralogy and Petrology, v. 69, p. 33-47.

Williams, H., Turner, F. J., and Gilbert, C. M., 1982, Petrography an introduction to the study of rocks in thin section: San Francisco, W. H. Freeman and Company, p. 26, 32-33, 96, 100-108, 116, 256.

Wilson, T. J., Grunow, A. M., Hanson, R. E., and Schmitt, K. R., Subduction complex rocks on Diego Ramirez Islands, Chile: Proc., 5th International Symposium on Antarctic Earth Science, Cambridge University, (in press).